Bone-Shaped Short Fiber Composite

A New Concept to Solve the Low Toughness and Strength Problem

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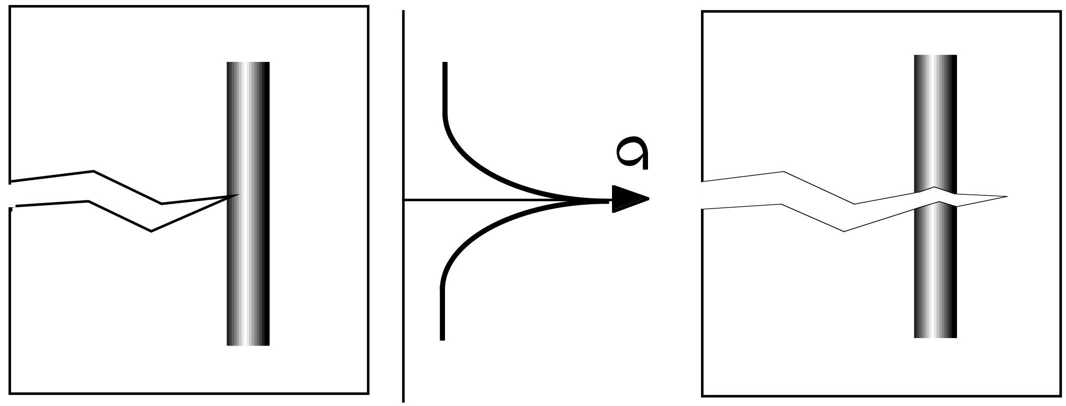
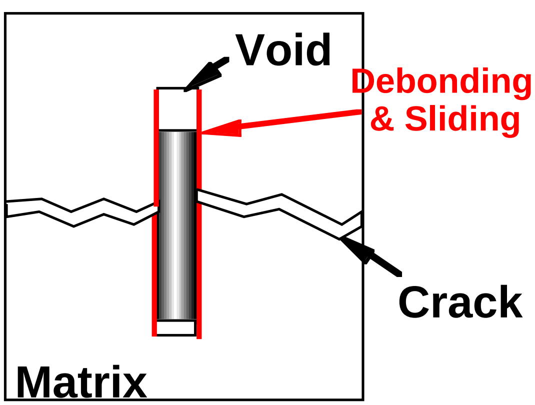
Problems with conventional composites

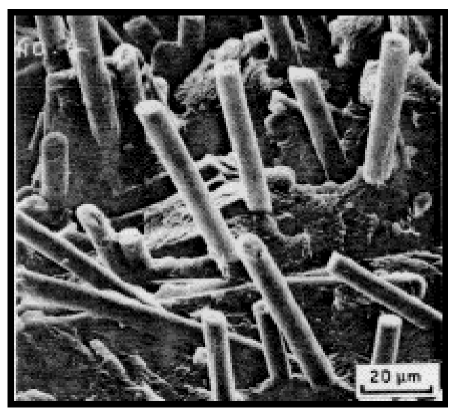
- Continuous fiber composites
  - Partial debonding relieves stress concentration
  - High strength and toughness
  - Expensive to fabricate
- Short-fiber composites
  - Less expensive (can be adapted to conventional manufacturing techniques)
  - Low strength
  - Low toughness

Paradox in designing the interfacial strength of conventional short straight (CSS) fiber composites

Strong interface:
Fiber breakage leads to low toughness





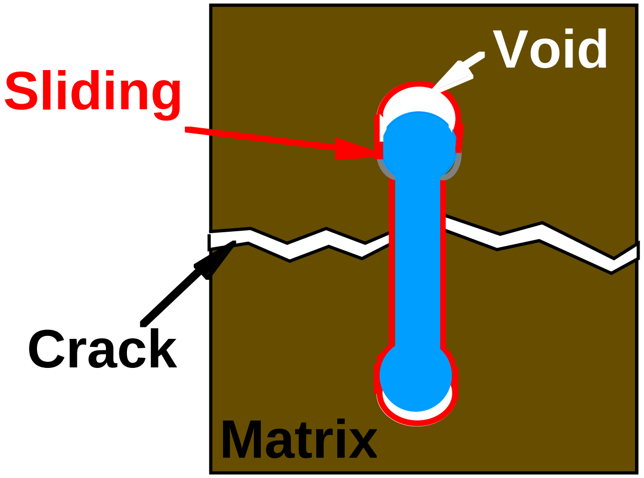


Weak interface:
Fiber pull out leads to low strength

Bone-Shaped Short (BSS) Fibers

A New Reinforcement Concept

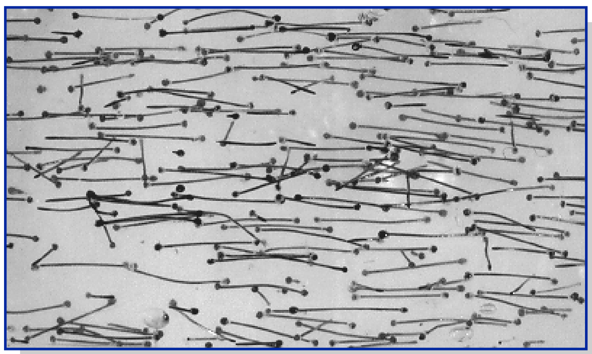
- Load transfer through mechanical interlocking
- Weak interface
  - Allows debonding for toughness
  - Does not affect load transfer
- With optimum shape and size
  - Fiber pullout at a stress close to fiber strength
    - **Consumes more energy**
- Results:
  - *Combined high strength and toughness*



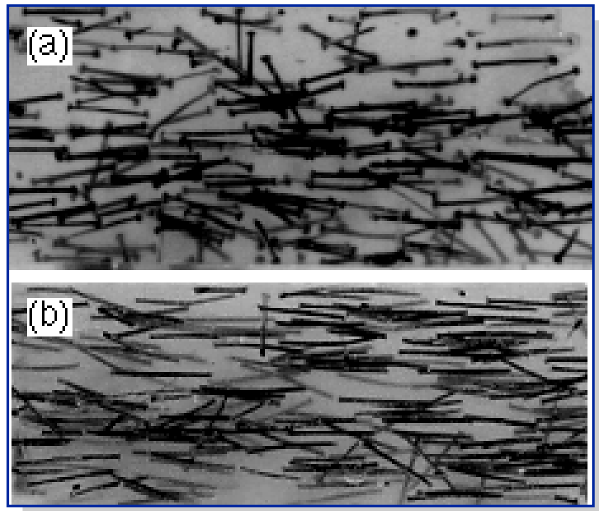
BSS-fiber composites with good fiber alignment were fabricated

- Model Material Systems:

  Reinforcements: polyethylene or Ni filaments
  Matrix: Polyester



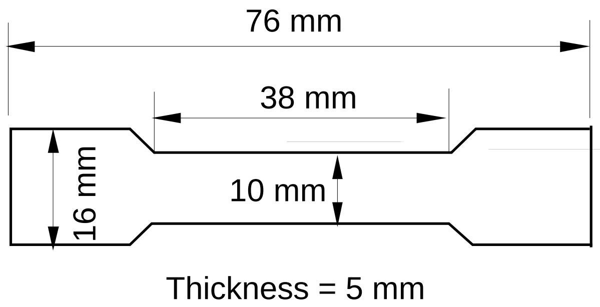
Bone-shaped Ni fiber reinforced polyester (V_f = 2.5%)



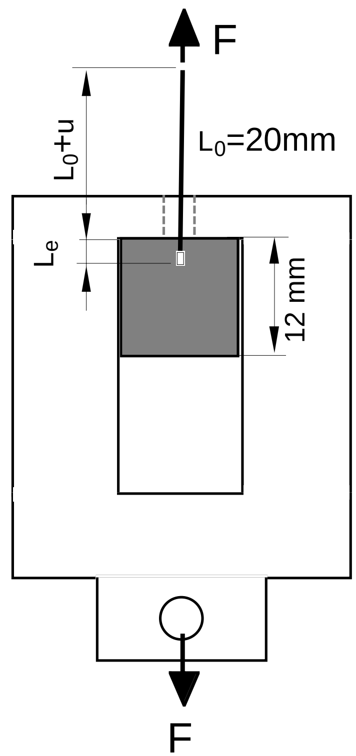
Polyethylene fiber reinforced polyester (V_f = 5%)

a) Bone-shaped short fiber composite
b) Straight short fiber composite

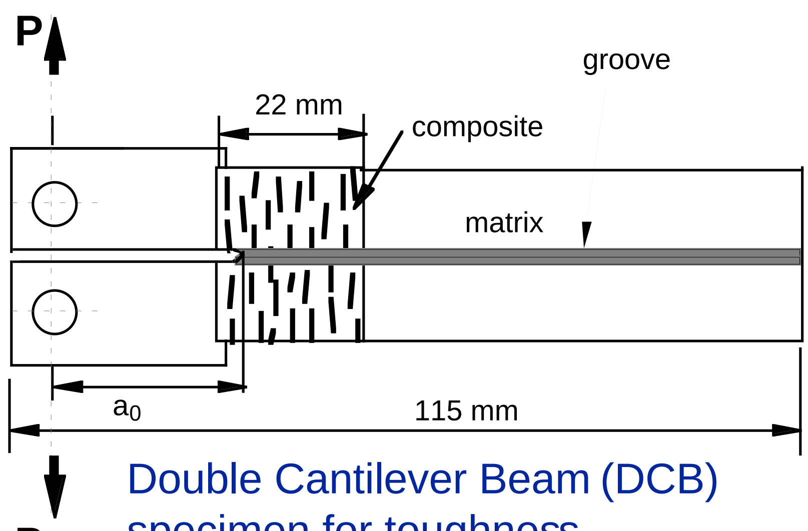
Mechanical Testing



Tensile testing specimen for strength

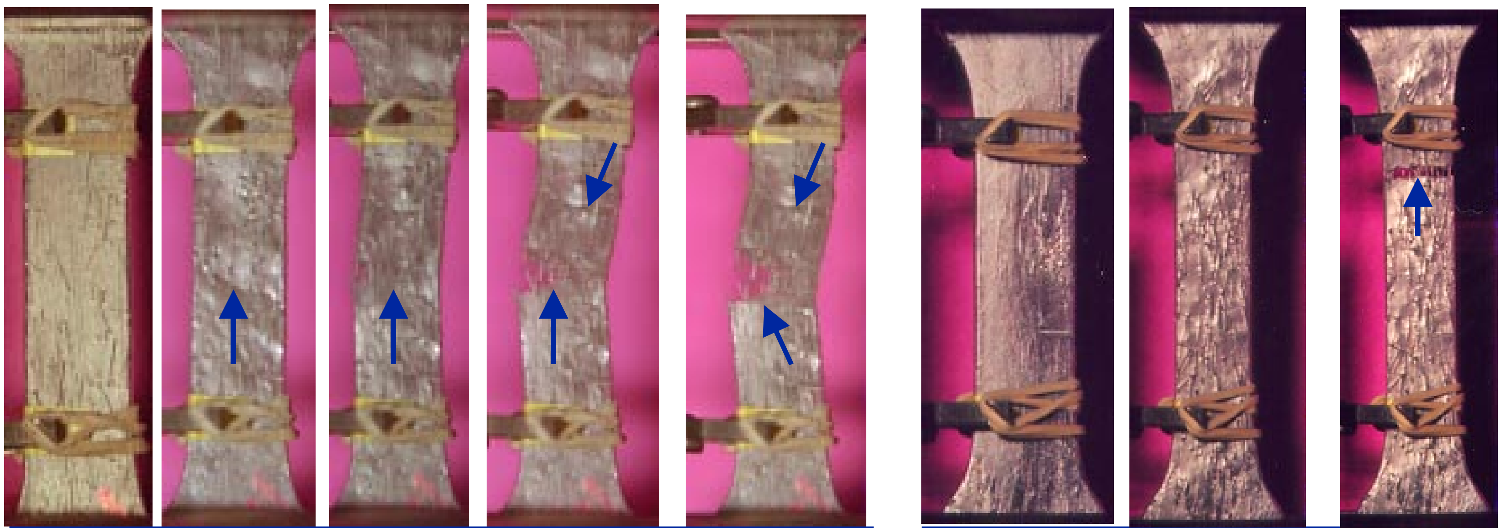


Fiber pullout test for bridging law



Double Cantilever Beam (DCB) specimen for toughness

Tensile tests show better crack bridging By BSS fibers



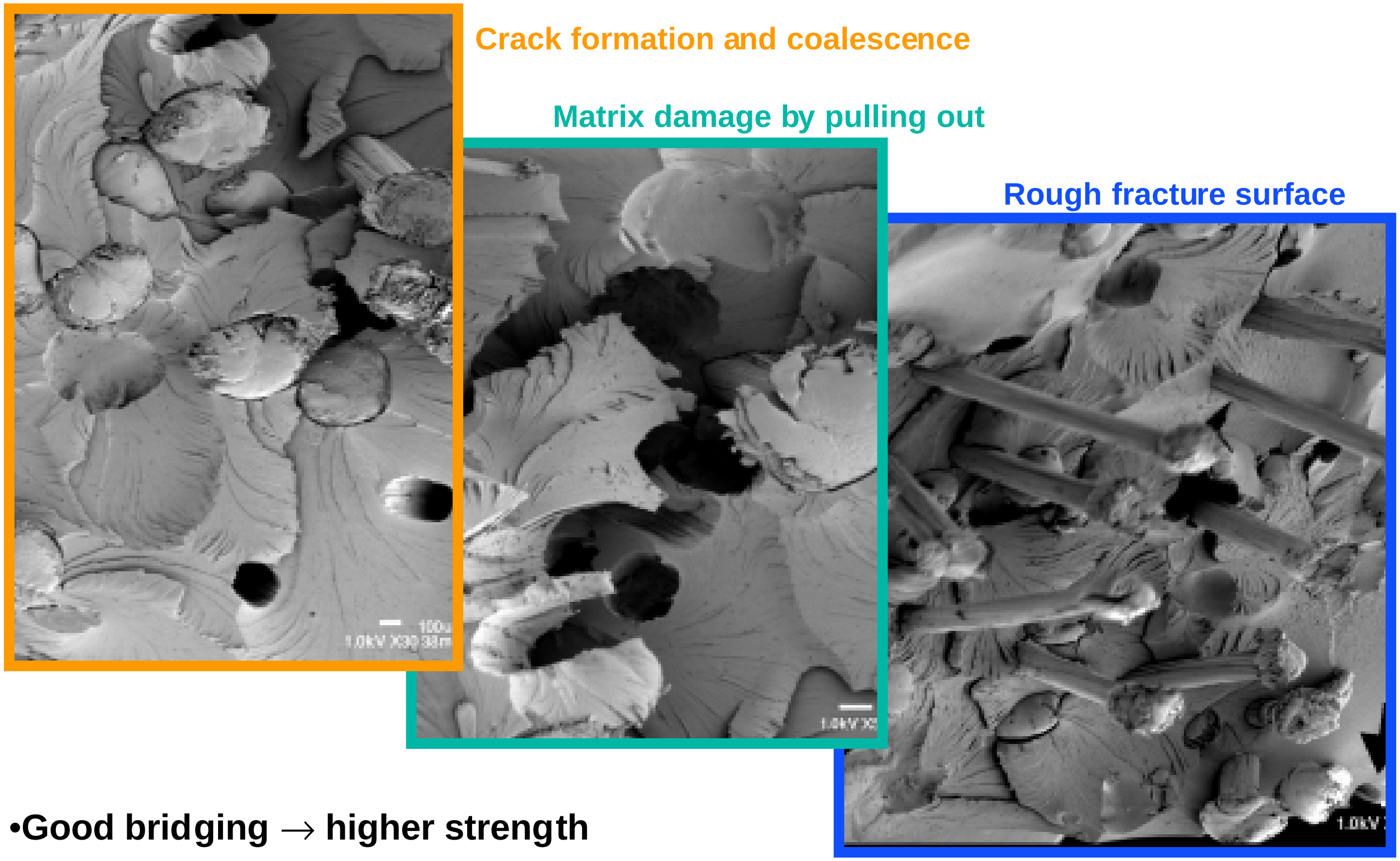
BSS-fiber composite

CSS-fiber composites

ε = 0% 5% 13% 17% 20% 0% 18% 20%

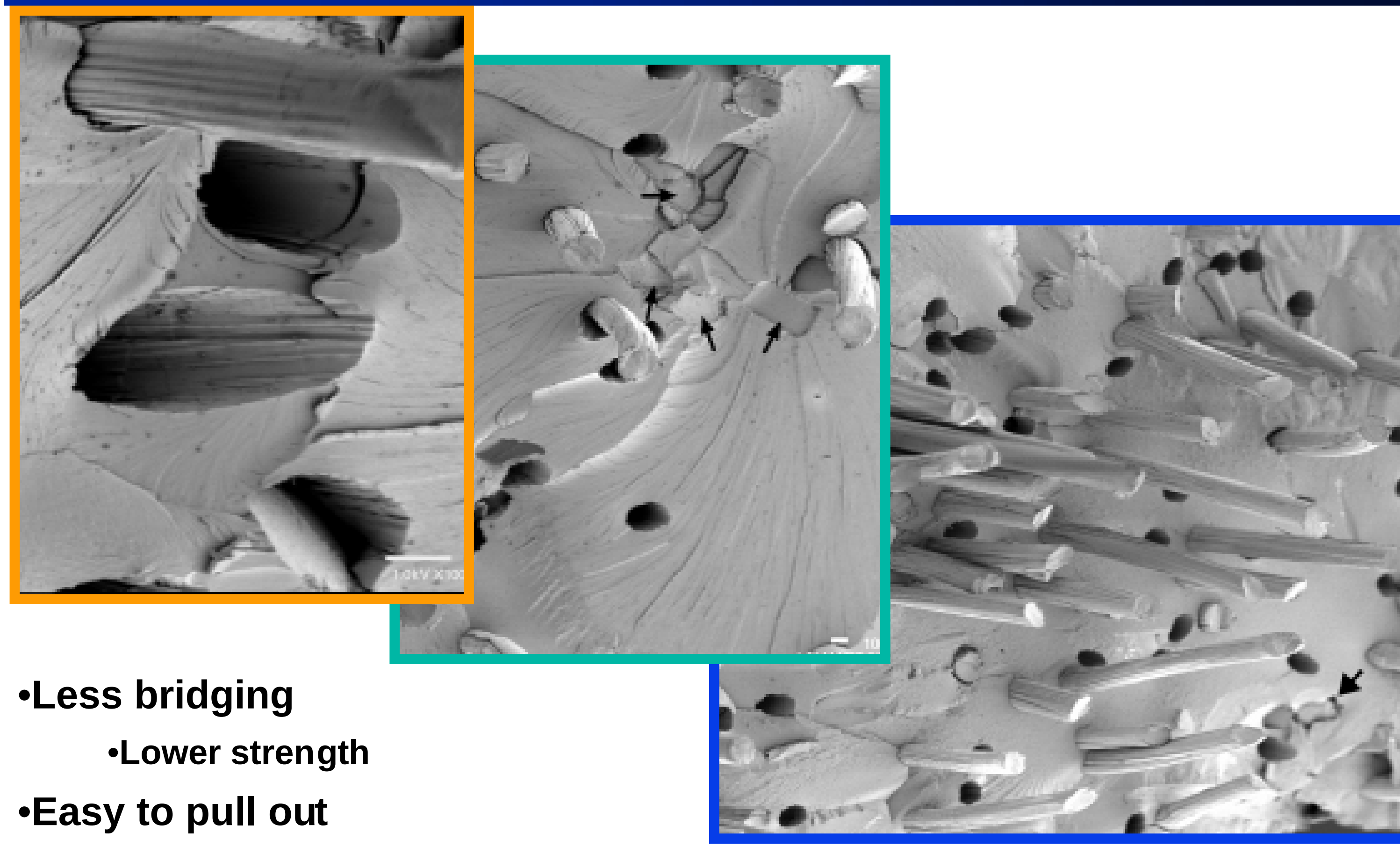
A BSS-fiber composite shows good bridging and multiple matrix cracking

Fractographs of BSS-fiber composites



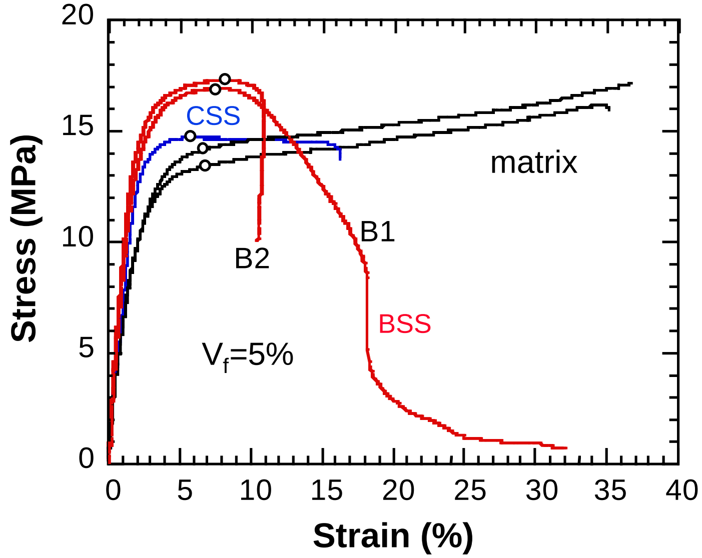
- Good bridging $\rightarrow$ higher strength
- Rough fracture surface $\rightarrow$ higher toughness
- End geometry promotes crack formation, can be solved by geometry design
- River marks indicate that the matrix is crack sensitive

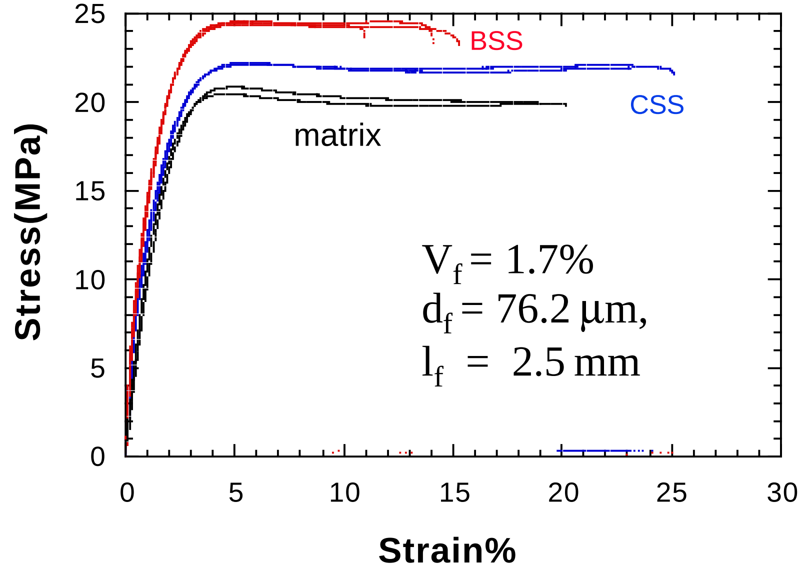
Comparison: Fractographs of CSS-fiber composites



- **Less bridging**
    - **Lower strength**
- **Easy to pull out**
- **Flat fracture surface**
    - **Crack propagated by the extension of the main crack**
- **River marks indicate that the matrix is crack sensitive**

Tensile stress and strain curves of BSS and CSS fiber composites



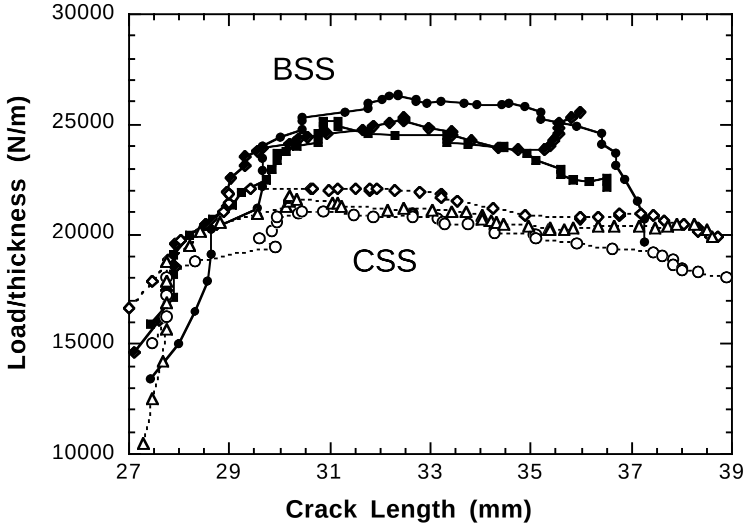


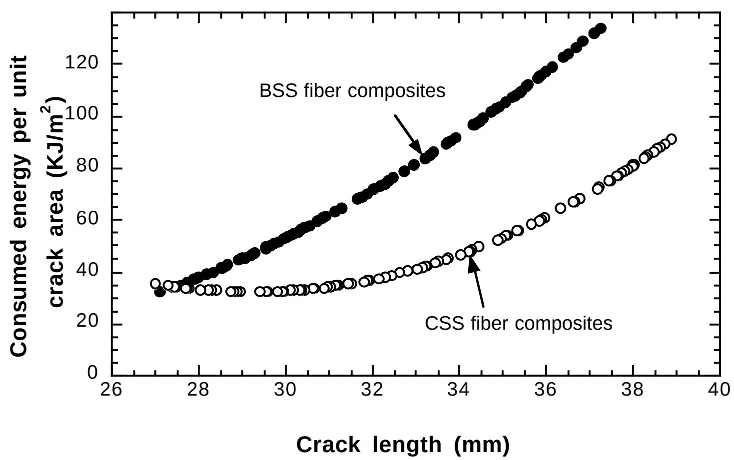
Polyethylene Fiber Composites:
A BSS fiber is 220% more effective than a CSS fiber

Ni fiber composites:
A BSS fiber is 170% more effective than a CSS fiber

- **Tensile testing results show that BSS composites have**
  - **Higher strength**
  - **Higher Young's modulus**

BSS-Fiber composites have higher fracture toughness





Fracture toughness

= Resistance to crack propagation

= Energy required to propagate crack by a unit area

- **Higher load is required for the crack to propagate in BSS-fiber composites than in CSS-fiber composites**
- **Higher energy is consumed per unit crack area for DCB samples made of BSS-fiber composite**

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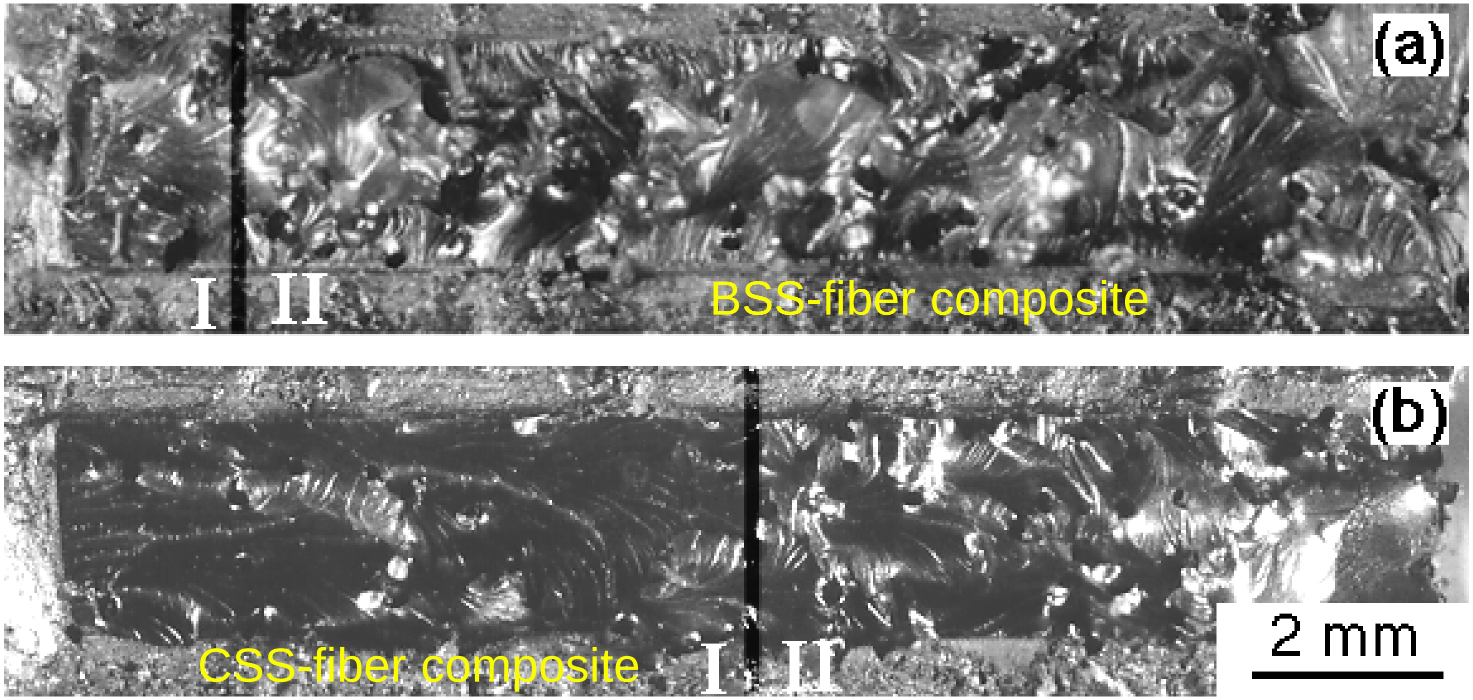
Topography of the DCB crack surfaces



Region I: Smooth surface: Crack propagated by the extension of the main crack (left of the dark line)
Region II: Rough surface: Crack propagated by the coalescence of smaller cracks with the main crack (right of the dark line)

- **Region II was caused by fiber-bridging of the main matrix crack**
- **Shorter Region I in BSS-fiber composite indicates better crack-bridging capability of BSS fibers**

Fiber pulling out tests point to much higher potential for improving both composite strength and toughness by BSS fibers

For embedded length L_e = 3.5 mm:

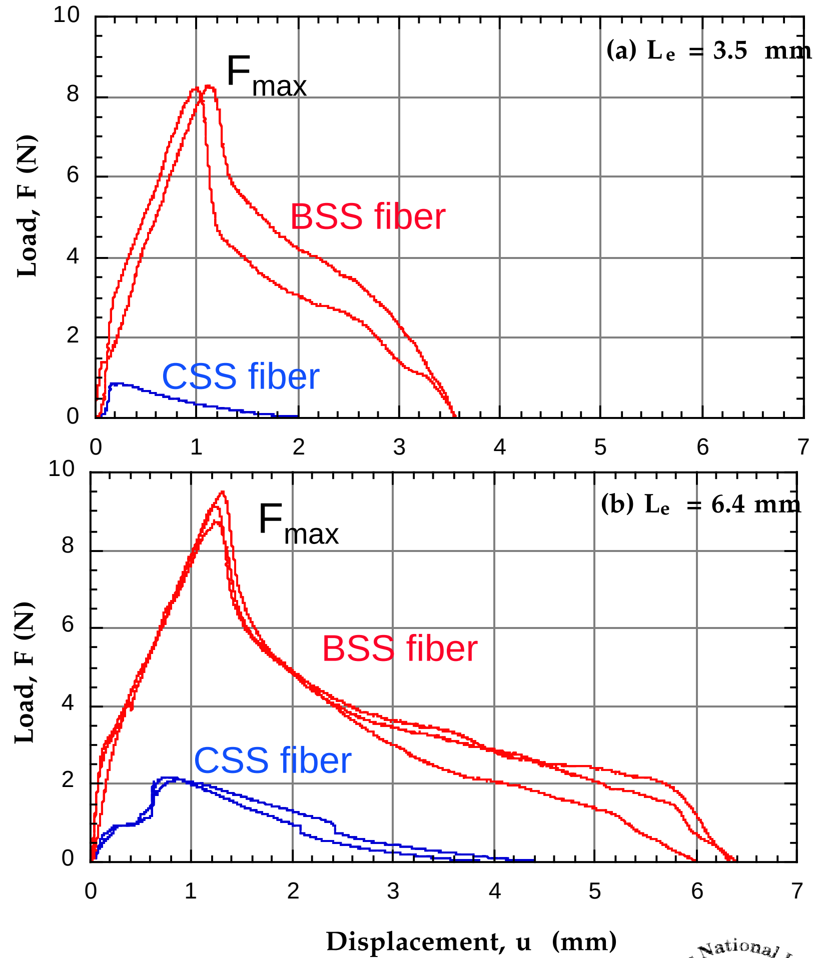
$$\frac{F_{\max}(BSS)}{F_{\max}(BSS)} = 9 \qquad \frac{Energy(BSS)}{Energy(CSS)} = 17$$

For embedded length L_e = 6.4 mm:

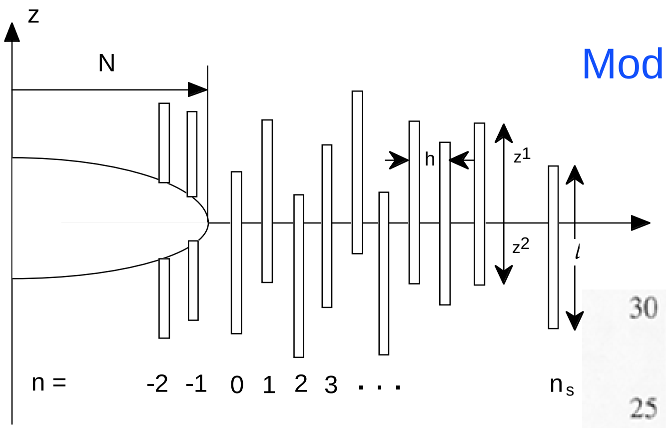
$$\frac{F_{\max}(BSS)}{F_{\max}(CSS)} = 4 \qquad \frac{Energy(BSS)}{Energy(CSS)} = 6$$

- **BSS fibers need much more force to be pulled out**
  - **More potential for improving composite strength**

- **BSS fibers consumes much more energy during pullout**
  - **More potential for improving composite toughness**

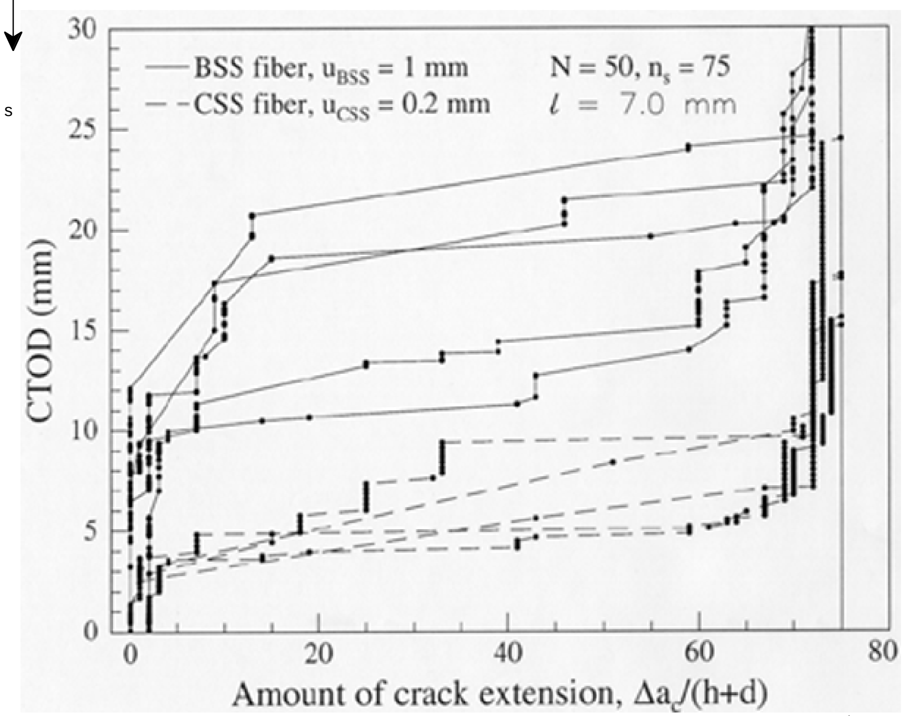


Statistical modeling agrees with experimental results:
BSS-fiber composites have higher resistance to crack propagation



Model composites for modeling

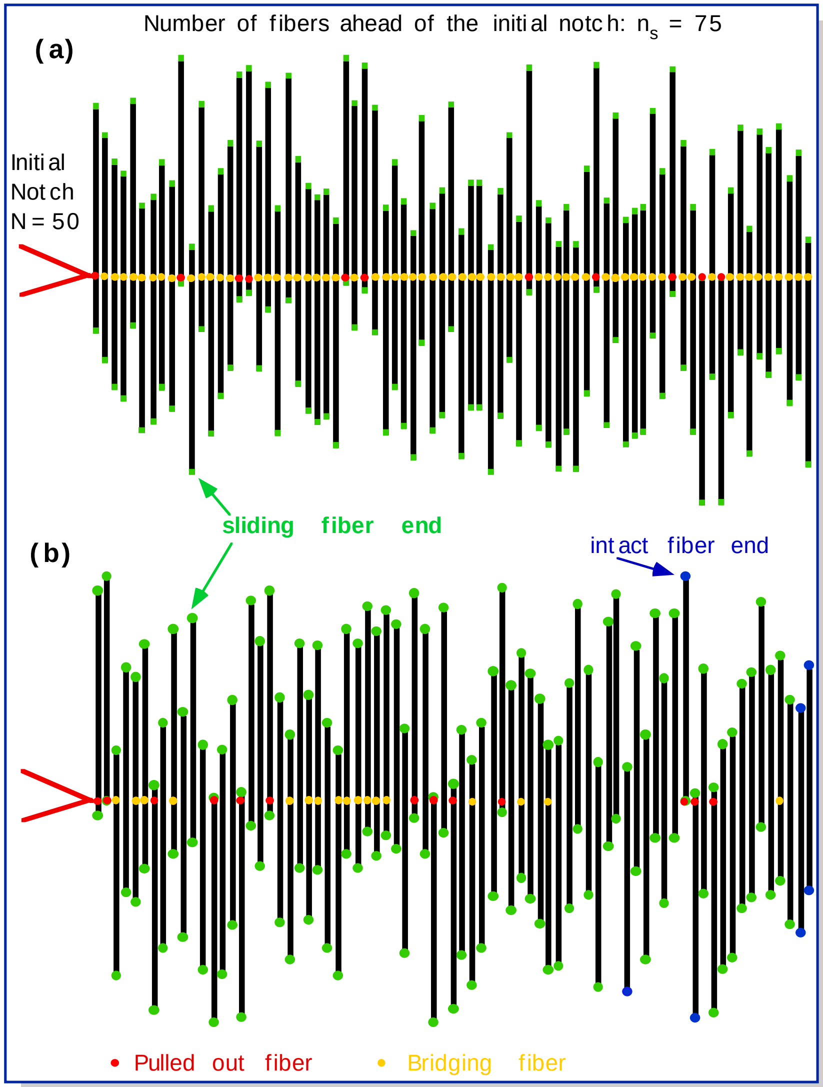
CTOD = crack tip opening displacement



- **Higher CTOD for the BSS-fiber composites means:**
  - **Higher force is required for crack propagation**
  - **Better crack bridging capability by BSS fibers**
  - **Higher fracture toughness**

Snap shots of a stage in crack propagation:

The BSS fiber composite has better crack bridging than CSS-fiber composite



Simulation results:

Under the same normalized load:

(a) The CSS fiber composite has a main crack with the number of bridging fibers n_B =75 (all way through)

(b) The BSS fiber composite has a main crack with n_B = 3 and secondary cracks ahead of the main crack

Discussion and Summary

- CSS-fiber composites:
  - **Fibers were not effective in crack bridging and load transfer**
    - **Low strength**
    - **Low toughness**
  - **Crack propagated by the extension of the main crack**
    - **Flat fracture surface $\rightarrow$ low toughness**
- BSS-fiber composites:
  - **Fibers were effective in crack bridging and load transfer**
    - **High strength**
    - **High toughness**
    - **High Young's modulus**
  - **Crack propagated by the coalescence of the main crack with secondary cracks ahead of the main crack**
    - **Rough fracture surface $\rightarrow$ high toughness**
  - **Cracks were initiated at ball ends and coalesced to form a large unstable crack**
    - **Early crack formation**
    - **Can be avoided by optimizing the morphology of fiber ends**

Discussion and Summary

- The polyester matrix showed brittle behavior in resisting crack growth. More crack-growth-resistant matrix such as metals and weak interfaces would further increase the performance of BSS-fiber composites

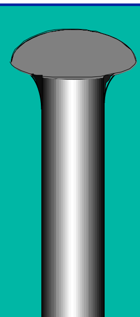
- Single-fiber pull out results indicate the potential for much more improvement in the strength and toughness than obtained in the current study

- Computational modeling is a valuable tool in optimizing processing parameters such as selection of matrix, fiber and interfacial properties as well as fiber morphology

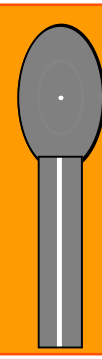
- BSS-fiber composites have the potential to solve the *intrinsic* low toughness and strength problem of CSS-fiber composites

Future Work

- Optimization of BSS-fiber morphology and selection of constituents properties
  - Computational modeling of the crack propagation
  - Finite Element Analysis of different fiber morphologies
- Investigation of crack bridging mechanics and pullout process of BSS-fibers
  - Analytical and computational



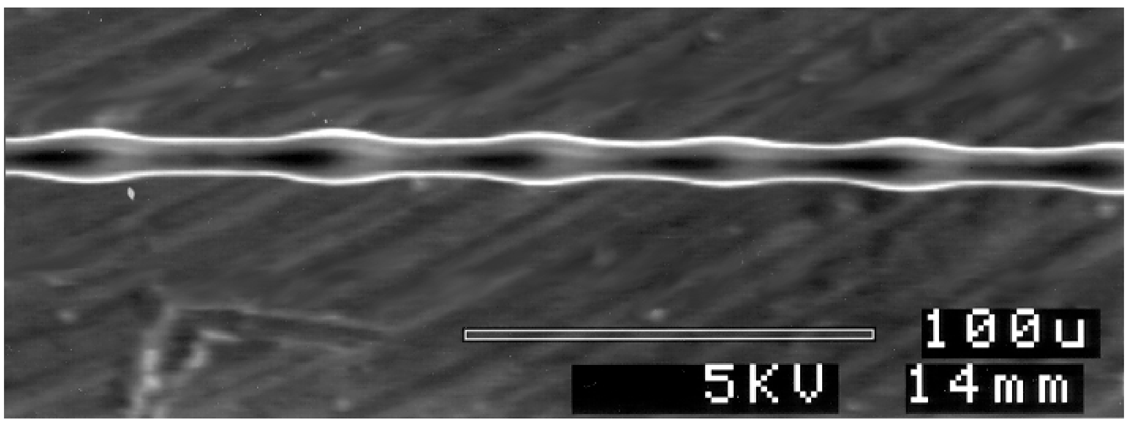
Current polyethylene fiber end promotes crack in matrix



Ideal morphology allow fiber pullout while consuming more energy

Future Work

- Development of commercial BSS-fibers
  - Commercial technology exists to make such fibers
  - Potential fiber candidates:
    - **Al_2O_3, SiC, Mullite, Si_3N_4, etc.**



- Development of commercial composite systems
  - Matrix: polymer, metal, and ceramics